The effect of longitudinal fluctuation in event-by-event (3+1)D hydrodynamics

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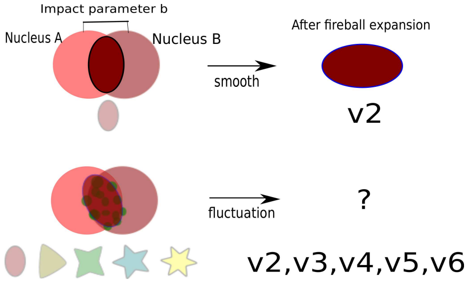
    - Why fluctuation initial condition and E-By-E hydrodynamics?
    - Introduction to 3+1D hydrodynamic simulation
    - AMPT initial condition
    - Spectra and elliptic flow at RHIC and LHC
    - Effect of transverse and longitudinal fluctuation(LF)
    - The relationship between di-hadron correlation and v_n
    - SUMMARY

Collision geometry and harmonic flow in relativistic heavy ion collisions.

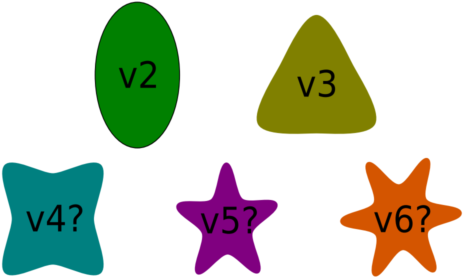
Smooth and fluctuating initial condition



$$\frac{dN}{dY p_T dp_T d\phi} = \frac{g_s}{(2\pi)^3}\int_\Sigma p^\mu d\Sigma_\mu \frac{1}{\exp((p\cdot u-\mu)/T_{FO})\pm 1} \quad (1)$$

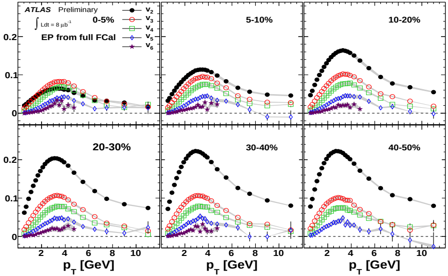
$$= N_0(1+2\sum_{i=1}^{\infty} v_n\cos(n(\phi-\Psi_n))) \quad (2)$$

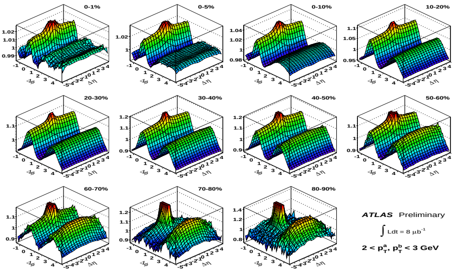
Decomposition of the initial collision geometry.



- The transverse distribution in fluc ini can be decomposed in different shapes.
- v_2 and v_3 have linear response to initial geometry eccentricity ε_2 and ε_3.
- High order harmonic flows do not. Zhi Qiu, U. Heinz, Phys.Rev. C84 (2011) 024911
- For non central collisions, v_4, v_5 may also depend on ε_2^2, $\varepsilon_2\varepsilon_3$. Phys.Rev. C85 (2012) 024908

The recent experimental data for v_n and di-hadron correlation





- Higher order harmonic flows and di-hadron correlation can only be studied with fluctuating initial condition in E-By-E simulation.
- Fluctuating initial condition has important effect on p_T spectra and v_2.(shown latter)

Hydrodynamics for Relativistic Heavy Ion Collisions

Main task: solve e, P, n, v_x, v_y, v_z from the following equations.

$$\partial_\mu T^{\mu\nu} = 0 \tag{3}$$
$$\partial_\mu J^{\mu} = 0 \tag{4}$$
$$P = EOS(e, n) \tag{5}$$

where:

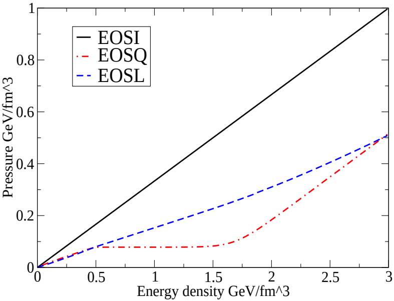
- $T^{\mu\nu} = (e+P)u^\mu u^\nu - P g^{\mu\nu}$
- $J^\mu = n\ u^\mu$.
- e: energy density
- P: pressure
- n: net baryon number density
- u^μ: four velocity which obeys $u_\mu u^\mu = 1$.

Hydrodynamics for Relativistic Heavy Ion Collisions III

We use (τ, x, y, η_s) coordinates,

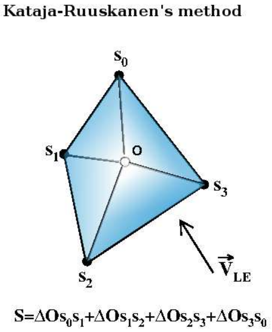
- Proper time $\tau = \sqrt{t^2 - z^2}$.
- Spacial rapidity $\eta_s = \frac{1}{2}\ln(\frac{t+z}{t-z})$.
- Rapidity $Y = \frac{1}{2}\ln(\frac{E+P_z}{E-P_z})$.
- Pseudo-rapidity $\eta = \frac{1}{2}\ln(\frac{P+P_z}{P-P_z})$.

Equation Of State



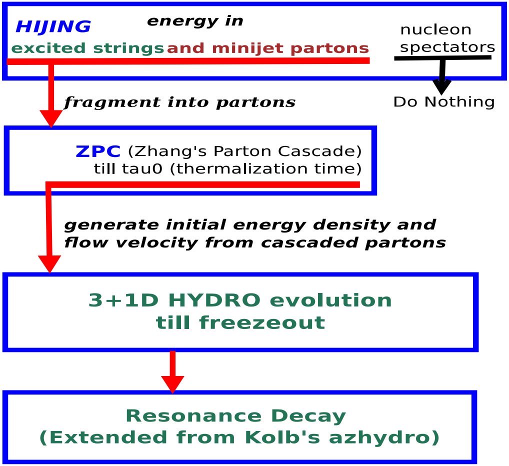
- EOSI: Massless ideal partons gas $p = e/3$.
- EOSQ: First order phase transition between QGP and HRG
- EOSL: Smoothed crossover between lattice QCD Eos and HRG
- We used EOSL parameterized in Nucl.Phys. A837 (2010) 26-53

Frz out hypersurface calculation:



- Kataja-Ruuskanen's method is used in Azhydro0p2 and Bjorn's $3+1$D hydro.
- Our projection method is much easier to extend to $n+1$D.
- Both methods save a lot of cpu hours in E-b-E calculation.

AMPT initial condition



Get $T^{\mu\nu}$ from cascaded partons

$$T^{\mu\nu} = K \sum_i \frac{p_i^\mu p_i^\nu}{p_i^\tau} f \qquad (6)$$

$$f = \frac{1}{\tau_0 \sqrt{2\pi\sigma_{\eta_s}^2} 2\pi\sigma_r^2} \exp\left(-\frac{(x-x_i)^2+(y-y_i)^2}{2\sigma_r^2} - \frac{(\eta_s-\eta_{si})^2}{2\sigma_{\eta_s}^2}\right) \qquad (7)$$

- We assumed local thermalization and solve e and u^μ from $T^{\mu\nu}$.
- We get K and τ_0 from fitting the multiplicity of charged hadrons at central collisions.
- $K = 1.45$ and $\tau_0 = 0.4$ fm for RHIC
- $K = 1.6$ and $\tau_0 = 0.2$ fm for LHC
- Longitudinal fluctuation and initial flow velocity are introduced in our simulation.

Fluctuation sources

AMPT: Energy density and flow velocity fluctuation

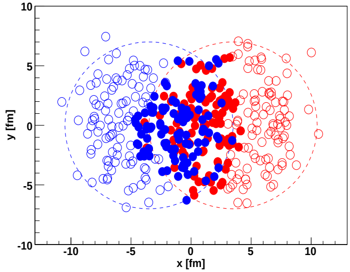
- Fragmentation and melting of strings.
- Mini-jets from binary collisions.
- Parton cascade.

Other fluctuation initial conditions

- MC Glauber and MC KLN: transverse energy density fluctuation
- URQMD ini: energy density and flow velocity fluctuation from hadrons.
- NeXSPheRIO: energy density and flow velocity fluctuation
- EPOS: energy density and flow velocity fluctuation

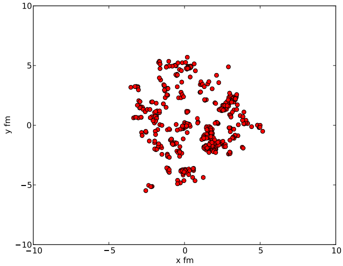
Transverse distribution

MC Glauber initial condition



$e(x, y, \eta_s) = H(\eta_s) * K * (\alpha n_{bc} + (1-\alpha) n_{wn})$.

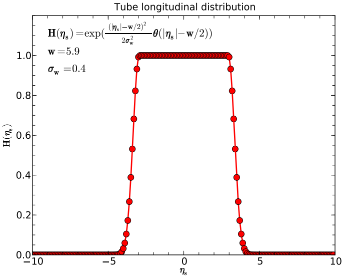
AMPT initial condition



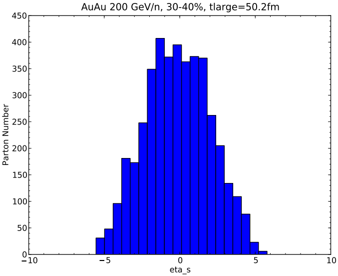
Get $T^{\mu\nu}$ from cascaded partons 4 momentum and spacial distribution.

Longitudinal distribution

Tube like longitudinal distribution



AMPT partons η_s distribution

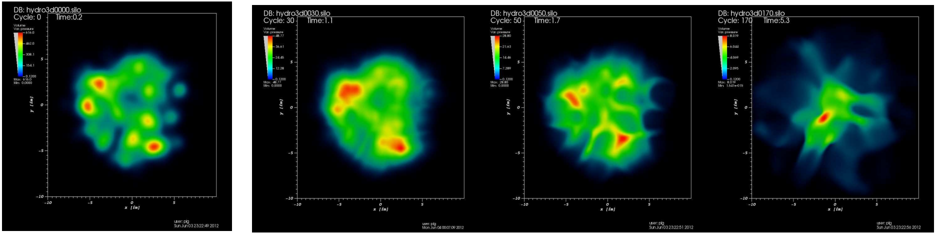


What do we want to see with AMPT ini condition?

- The effect of longitudinal fluctuation on transverse evolution.
- 2+1D (Bjorken scaling) .vs. 3+1D (Tube, Fluc)
- Flow velocity fluctuation.
- Two particle correlation.

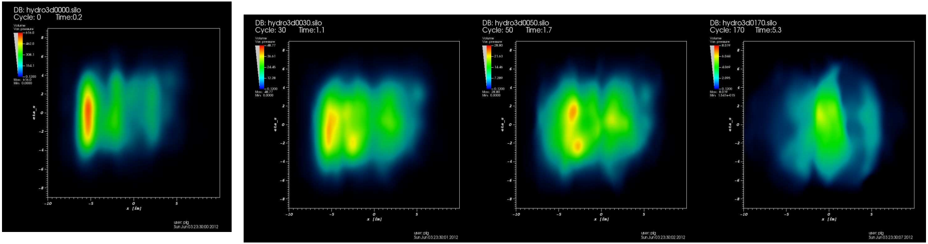
Hydrodynamic evolution for AMPT initial condition I

Transverse plane ▸ Youtube Link

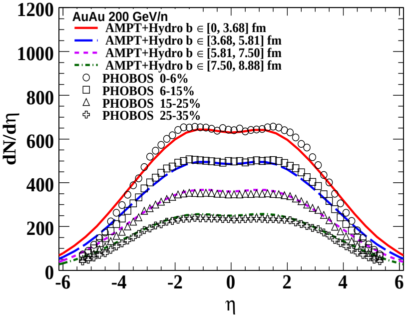


Hydrodynamic evolution for AMPT initial condition II

Reaction plane Youtube Link

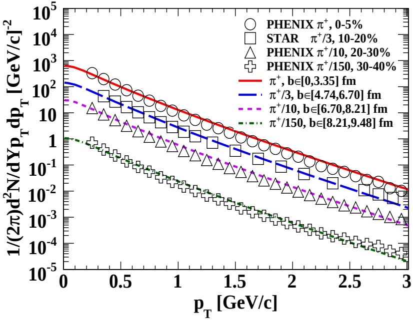


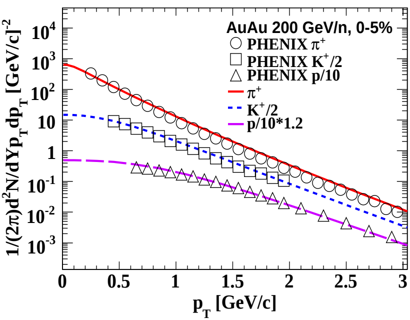
(RHIC) Centrality dependence of multiplicity and p_T spectra



- 3+1D viscous hydro will give a wider shoulder at central rapidity. Bjorn, Phys. Rev. C **85**, 024901 (2012) Piotr, Phys. Rev. C **85**, 034901 (2012)
- We did not consider net baryon density at large rapidity yet.

(RHIC) p_T spectra





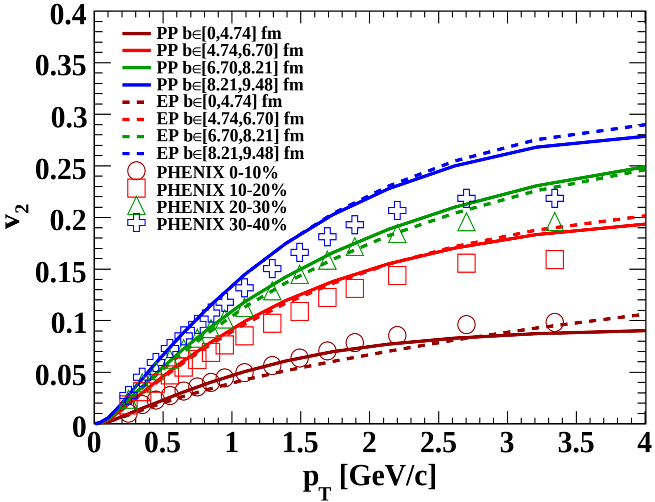
- We used Chemical Equilibrated EOS(s95p-v1) and underestimated proton production.
- Partial Chemical Equilibrated EOS will fix this at RHIC energy.
- PCE EOS fails to describe LHC results.

(RHIC) Calculate v_2 from Participant Plane(PP) and Event Plane(EP)

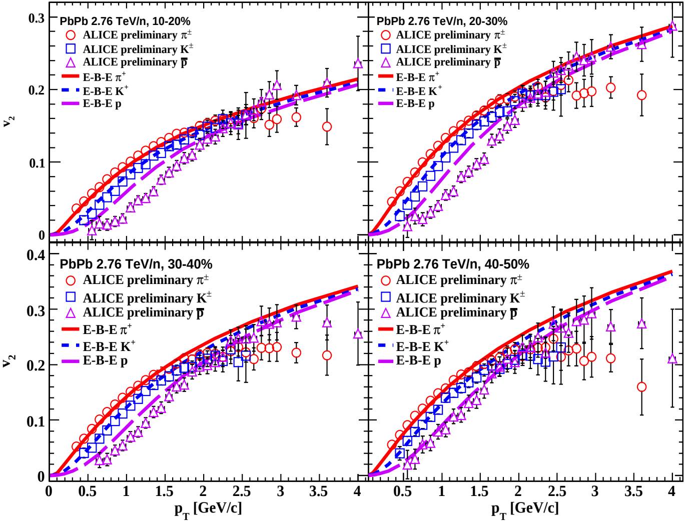
$$v_2 = \frac{\int \cos(2(\phi - \Psi_n)) \frac{dN}{dY p_T dp_T d\phi} d\phi}{\int \frac{dN}{dY p_T dp_T d\phi} d\phi} \tag{8}$$

- PP: $\Psi_n = \frac{1}{n}(\arctan \frac{\langle r^n \sin(n\phi_r)\rangle}{\langle r^n \cos(n\phi_r)\rangle} + \pi)$
- EP: $\Psi_n = \frac{1}{n} \arctan \frac{\langle p_T \sin(n\phi_p)\rangle}{\langle p_T \cos(n\phi_p)\rangle}$
- These two definitions should give out similar results.
- We use the continues particle spectra to calculate EP, no resolution problem.

(RHIC) Elliptic flow for EP, PP method compared with Exp.



(LHC) The elliptic flow for identified particles.



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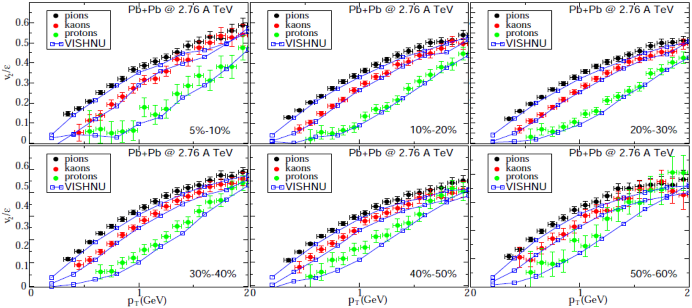
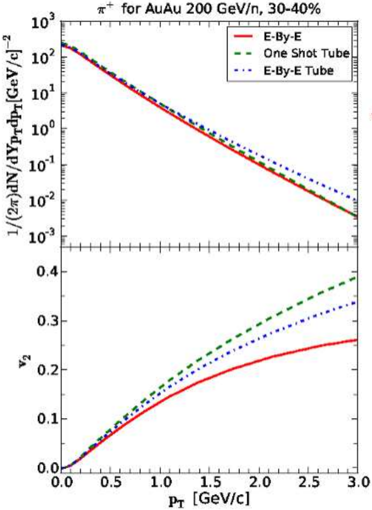


FIGURE 5. (Color online) Same preliminary data from ALICE [20, 21] as in Fig. 4, but now compared with VISHNU calculations with $(\eta/s)_{QGP} = 0.2$, using the same MC-KLN initial conditions as in Fig. 3. Shown is the eccentricity-scaled elliptic flow, *i.e.* $v_2\{2\}/\varepsilon_x\{2\}$ for the experimental data and $\langle v_2\rangle/\langle\varepsilon_x\rangle$ for the theoretical curves.

- Figure from AIP Conf.Proc. 1441 (2012) 766-770 by Ulrich W. Heinz, Chun Shen and Huichao Song.
- Pure hydro has the proton v_2 puzzle for central collisions.
- Viscous hydro + URQMD may give a better fit for proton v_2 at central collisions.

Fluctuation effect



E-By-E Tube

transverse fluc ↗ ↘ longitudinal fluc

One Shot Tube E-By-E

One Shot Tube

↓ transverse fluc

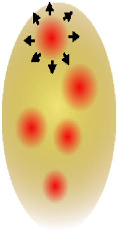
E-By-E Tube

↓ longitudinal fluc

E-By-E

Effect of transverse energy density fluctuation

Fast isotropic expansion of each hot spot at early stage in transverse plane



Harder p_T spectra and smaller v_2 at large p_T.

- R. Chatterjee, H. Holopainen, T. Renk, and K. J. Eskola Phys.Rev. C83 (2011) 054908
- B. Schenke, S. Jeon, C. Gale, Phys. Rev. Lett. 106, 042301
- Z. Qiu and U. W. Heinz, Phys. Rev. C 84, 024911
- Also seen in our AMPT initial condition

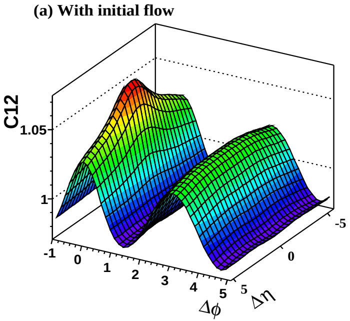
Effect of longitudinal fluctuation

- Non zero pressure gradient along η_s at central rapidity.
- Faster expansion along η_s direction for each hot spot.
- Suppress transverse expansion and v_2.

Effect of initial flow on di-hadron correlation

(AuAu 200 GeV/n Centrality $10-20\%$)

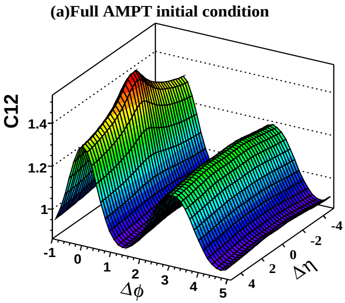
$$C_{12} = < N_1^t N_2^a >_{same} / < N_1^t N_2^a >_{mixed} \quad (9)$$

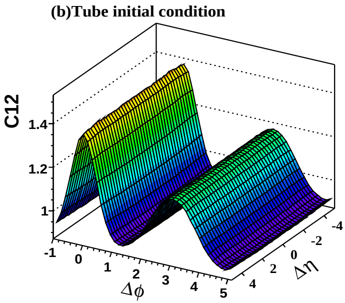


- Without initial flow, the di-hadron correlation is much flatter.

The effect of longitudinal fluctuation on di-hadron correlation

(AuAu 200 GeV/n Centrality $30 - 40\%$)

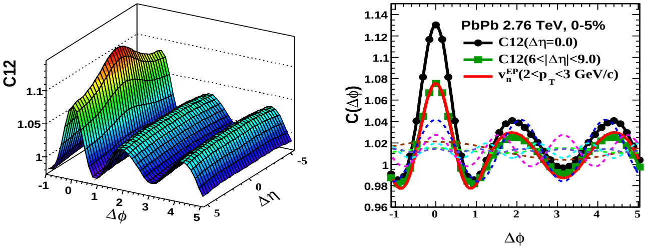




- Without LF, di-hadron correlation is constant along rapidity direction

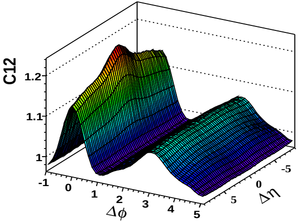
The decomposition of di-hadron correlation for AMPT+3DHydro simulation I

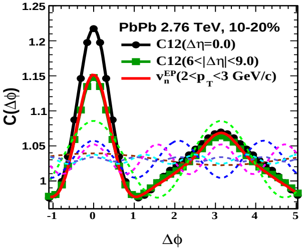
$$C12(\Delta\phi) = b_1 \cos(\Delta\phi) + b_2(1.0 + v_{n,t}^{EP} v_{n,a}^{EP} \cos(n\Delta\phi)) \tag{10}$$



- Di-hadron correlation at large $\Delta\eta$ can be decomposed in v_n.
- Since initial flow and LF is introduced in AMPT initial condition, short range correlation can't be decomposed in v_n.
- AMPT initial condition gives a wide near side peak(which must be studied further)

The decomposition of di-hadron correlation for AMPT+3DHydro simulation II





- For different centralities, the weight of harmonic flow will be different, so as the away side structure.

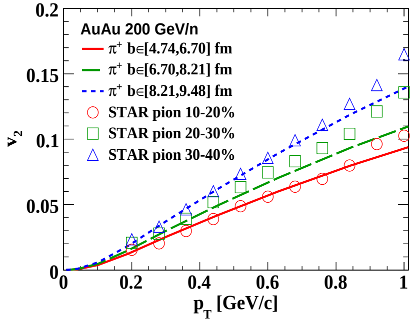
SUMMARY

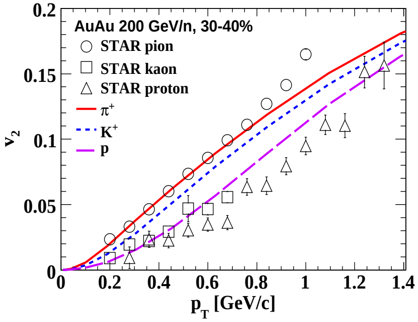
- We studied the E-by-E hydrodynamic simulation with AMPT initial condition.
- The E-by-E simulation gives good agreement with experiment data for spectra and elliptic flow.
- Fluctuation has important effect on p_T spectra and v_2.
  - TF: Fast isotropic expansion of each hotspot in transverse plane at early stage.
  - LF: Bigger longitudinal pressure gradient and expansion rate.
- LF and initial flow introduced by AMPT have important effect on two particle correlation.

Thanks!

Backup

(RHIC) Identified particles' elliptic flow





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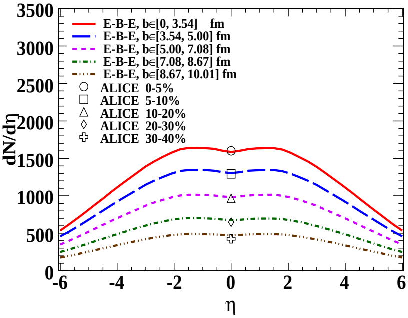
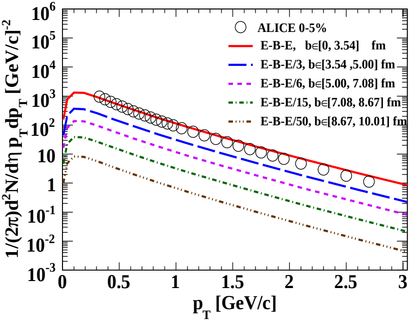
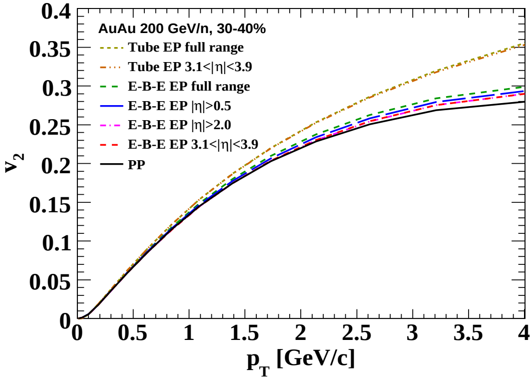




Event plane selection in event by event hydrodynamic simulation



- Rapidity range selection for EP doesn't matter for without LF
- With LF, EP at large rapidity will be smaller and closer to PP method.